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14. ABSTRACT

The subject research program sought to explore a novel method for achieving passive flow field control, with applications to mixing enhancement and noise reduction, through the interaction of the flow with flexible filaments. The filament was attached to a jet centerline where it was allowed to interact with and modify the large-scale structures in the flow. This flow control resulted in improved mixing, lower noise, and a more stable flow. The filament was shown to be particularly effective in suppressing screech in underexpanded supersonic jets. The study was successful in identifying an optimal filament configuration, which was used to obtain attenuation levels as high as 32dB. An investigation of temperature effects indicated that the filament performance was actually enhanced with moderate temperature increase. Sound field mappings revealed that the filament created dramatic changes in the sound field. Finally, flow field analysis of the supersonic jet revealed that the filament was successful in extensively modifying the structures in the exhaust plume, which can provide a physical explanation for the measured noise reduction. The researchers feel that this program was successful, as the results prove that the filament effectively attenuated jet noise in both supersonic and subsonic flows.

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FLOWFIELD MIXING ENHANCEMENT AND NOISE CONTROL USING FLEXIBLE FILAMENTS

AFOSR GRANT No. F49620-96-1-0378

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Abstract

The subject research program seeks to explore a novel method for achieving passive flow field control, with applications to mixing enhancement and noise reduction, through the interaction of the flow with flexible filaments. Figure 1 shows how a centerbody device is used to hold and align the filament along the centerline of the flow. A small knot is tied near the end of the filament in order to stabilize it in the flow.

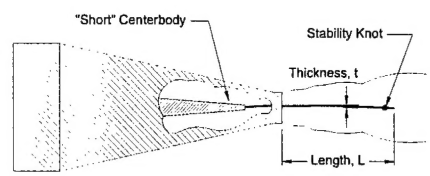


Figure 1: Attachment of Filament Using Centerbody Device

The primary purpose of the filament is to modify the large-scale structures within the flow[13]. These structures consist of the vortex formation in subsonic flow and the shock structure in supersonic flow. This flow control can result in improved mixing, lower noise, and a more stable flow. The primary objective of this research program was to expand on these results to fully develop this unique approach to flow field modification.

The researchers feel that the primary objective was accomplished as the results of this program prove that the filament is effective in attenuating jet noise in both supersonic and subsonic jets. The filament was shown to be particularly effective in suppressing screech in underexpanded supersonic jets. A parametric study of various filament parameters successfully identified an optimal filament configuration for maximum attenuation. With this optimal filament, attenuation levels of up to 32dB in peak noise were documented for some operating conditions. An investigation of temperature effects on the filament effectiveness indicated that the filament performance is actually enhanced with moderate temperature increase. Finally, a complete mapping of the jet near field showed that the filament creates dramatic changes in the sound field. For supersonic jets, the filament eliminates the strong directional gradients in overall sound pressure level (OASPL),

which are associated with screech tones. This produces a much more uniform and stable sound field. The peak OASPL was observed to be reduced by up to 12dB with an average attenuation level of approximately 10dB. A mapping of the near field of a subsonic jet indicated that the filament is successful in reducing turbulent mixing noise by as much as 2dB in the rear quadrant. Flow field analysis of the supersonic jet, using a stereoscopic PIV system, revealed that the filament is successful in extensively modifying the structures in the exhaust plume. The filament is observed to significantly weaken the shocks and reduce the spacing, as well as increasing the jet spread and reducing the downstream velocities. Each of these factors can be tied directly to the measured reduction in OASPL throughout the near field.

Objective

The main goal of the subject research program was to thoroughly investigate the use of flexible filaments for flow control applications. Specifically, the program seeks to achieve the following objectives:

1) *Understand the physical mechanisms governing the filament/flow interaction.* Developing an understanding of the mechanisms responsible for the filament induced flow modifications is crucial for exploiting the full potential of this concept.
2) *Determine the optimal filament configuration(s) for achieving the desired flow control.* There are numerous parameters associated with the filament including its material properties, geometry, size, attachment location, and the number of filaments used. Each of these parameters may influence the extent of flow field modifications. The impact of these parameters will be investigated as part of the project.
3) *Quantify the attainable flow enhancements/modifications.* The potential benefits of the filaments for noise control and mixing enhancement will be investigated to document the extent of the enhancements achievable.
4) *Identify additional applications for this concept.* During the course of the research program, efforts will be made to identify additional applications for this concept.

Approach

To execute the subject research program, a jet flow facility capable of producing both subsonic and supersonic flows was constructed. The facility is capable of primary flow Mach numbers up to approximately 2.0. Also, the primary flow may be heated to a stagnation temperature of 500°F. In order to facilitate accurate acoustical measurements, an anechoic chamber has also been constructed with a lower cutoff frequency of approximately 400 Hz. The chamber is fully instrumented with an array of high frequency condenser microphones. In addition, a traversing mechanism is available for complete mapping of the sound field. The layout of the microphone array as well as two separate areas covered by the sound pressure mapping is shown below in Figure 2.

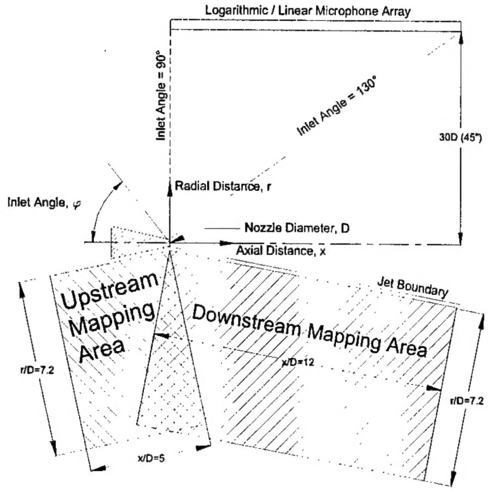


Figure 2: Layout of Microphone Arrays and Mapping Areas

Results

Filament Optimization

In order to address goal (2) and systematically determine the optimal filament configuration, a series of tests were performed with the jet operating at Mach 1.3 with no heating. Filament L/D ratios were varied from -0.75 to 10 in an effort to identify both a critical length required for any suppression and a length for optimal suppression. Note that since the centerbody device terminates two inches upstream of the nozzle exit and the filament length is reference from the nozzle exit plane, as shown in Figure 1, it is possible to have a negative filament lengths. Figures 3 and 4 show the narrowband spectra for selected filament lengths obtained with microphones at a radial distance of 30 primary diameters and inlet angles of 90° and 130° respectively.

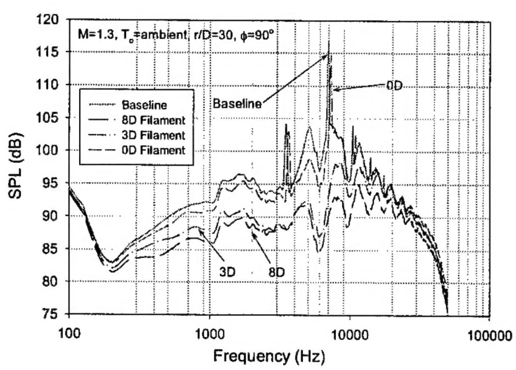


Figure 3: Spectra for Various L/D, ϕ= 90°

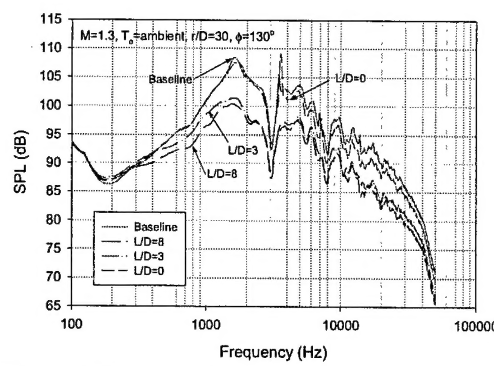


Figure 4: Spectra for Various L/D, ϕ= 1

While the dramatic suppression attainable with the longer filaments is clearly evident, note that some small attenuation can be observed with an L/D ratio of 0 (i.e. coincident with nozzle lip). Figure 5 summarizes the results of the length optimization for both inlet angles tested. While reductions as high as –22dB are observed with an L/D=8, the filament effectiveness begins to flatten out beyond L/D of approximately 3 to 4. This is particularly apparent at the downstream location where the filament effectiveness is more limited due to the absence of high screech amplitudes. For practicality reasons, the

optimal filament length was determined to be approximately L/D=3. However, it should be noted that additional attenuation is attainable with longer filaments if the length can be accommodated. To complete the filament optimization, the length was held constant at L/D=8 while the thickness was systematically varied. As Figure 6 shows, the filament performance was not as sensitive to variations in thickness as it was to variations in length. Basically, there is a minimum allowable thickness beyond which the filament becomes acoustically invisible. This threshold can be seen in Figure 6 to occur at about t/D=0.04. In most applications, the selection of the appropriate thickness should be made on the basis of strength requirements.

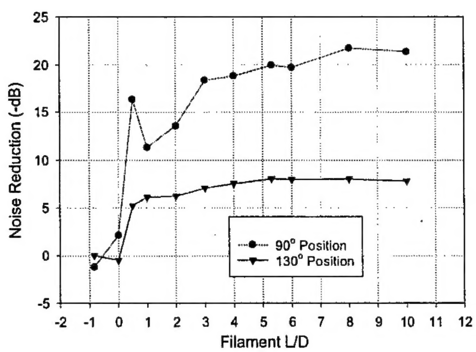


Figure 5: Filament Length Optimization Summary

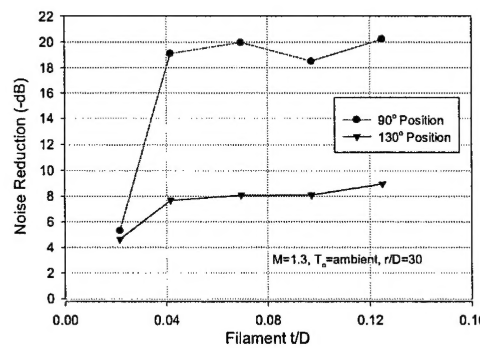


Figure 6: Thickness Optimization Summary

Temperature Effect on Filament Performance

Tests were also performed in order to observe any changes in the jet spectra with elevated temperatures. Specifically, acoustical data was collected with the jet at a Mach number of 1.3, with no filament attached over a range of temperatures from ambient to 500°F. These tests confirmed the previous findings of Massey and Ahuja, which indicated that the peak noise level of the jet should increase as temperature ratios are increased from 1.0 to approximately 1.8[2]. Next, these tests were repeated with an "optimal" filament of L/D=6 and t/D=0.08 attached in order to quantify the filament performance at elevated temperatures. The results of these tests as well as the baseline temperature effect tests are summarized below in Figure 7. The upper two curves show the baseline (no filament) peak SPL of the jet for inlet angles of 90° and 130° as the temperature increases. The two lower curves show the peak SPL of the jet for the same inlet angles when the optimal filament is attached. Notice the filament effect in the 90° direction. The filament reduces the peak SPL to approximately 97 dB and the dependence of this peak level on temperature appears to have been eliminated. This results in reductions of peak SPL ranging from 19 dB at ambient to an incredible 32 dB at a temperature of 425°F. Almost equally dramatic, the filament provides effective attenuation in the downstream direction ranging from 8 dB at ambient to 17 dB at 500°F. These results prove that increasing jet temperature does not mitigate the filament effectiveness and to the contrary, may actually improve it. Figure 8 shows a comparison of the baseline and optimal filament spectra obtained from the 90° microphone for the jet operating at M=1.3, T=425°F. The dramatic effect of the filament can be fully

appreciated from this figure. In addition to complete suppression of all screech tones, the SPL is attenuated across the entire frequency range with no crossover observed.

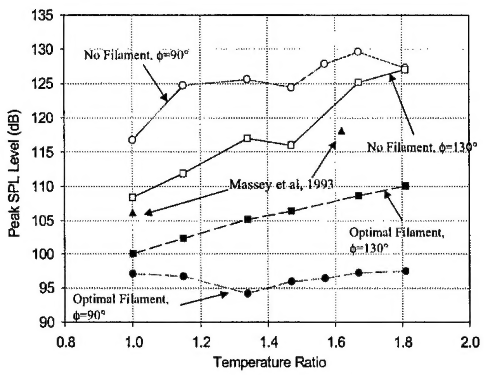


Figure 7: Summary of Temperature Effects

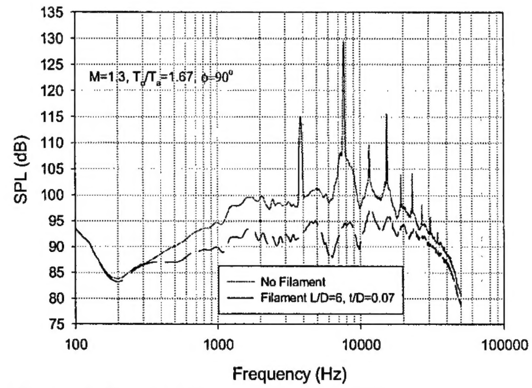


Figure 8: Spectra Comparison at 425°F

Near-Field OASPL Mapping

Finally, a complete mapping of the overall sound pressure level (OASPL) in the near field was completed in order to better understand the spatial effect of the filament on the overall sound pressure field. Refer back to Figure 2 for an explanation of the upsteam and downstream mapping areas. Figures 9-12 show a comparison of the baseline sound pressure fields with those obtained with the optimal filament attached. Figures 9 and 10 show the baseline upstream and downstream OASPL fields. The strong directional gradients, which are typical of an underexpanded supersonic jet, are clearly evident in these contour plots[3]. Also evident is the propagation of the fundamental screech tone in the upstream direction as well as the slightly weaker harmonic in the 90° direction. The fundamental screech tone seen in the narrowband spectra in Figures 3, 4, and 8 occurs at a Strouhal number of 0.3. By plotting the non-dimensional amplitudes of the fundamental screech tone and its first harmonic, the screech propagation is isolated and clearly illustrated. The non-dimensional amplitude of the fundamental screech tone is plotted in Figures 15 and 16 while the first harmonic is shown in Figures 17 and 18. These four plots show the preferential directional propagation of the screech tones as observed by previous researchers[5,6]. Specifically, the fundamental tone propagates primarily in the upstream direction at an inlet angle of approximately 45°, while the harmonic propagates roughly normal to the jet direction. Referring to the baseline jet near field shown in Figures 9 and 10, a peak OASPL of 152dB is observed to occur very near the nozzle lip.

Figures 11 and 12 show the near field for the same operating condition with the optimal filament attached. The differences between the baseline sound field and the treated sound field is quite dramatic. Immediately noticeable is an overall smoothing and stabilization of the sound field. The strong directional gradients seen in Figures 9 and 10 are for the most part eliminated and the peak OASPL is reduced by 12dB from 152dB to 140dB. Given the high screech amplitudes observed in the upstream grid in Figure 15, it is reasonable to conclude that this is the dominant mechanism behind the high OASPL levels and the strong directional gradients observed in this region in the baseline case (Figure 9). Now, referring to Figure 11, it is clearly evident that the filament has virtually eliminated these characteristics and thus appears to have attenuated the screech effect throughout the jet near field. While, a weak harmonic is still recognizable with the

filament attached in Figure 12, it is easy to see that the dominant noise generation mechanism is now the turbulent mixing noise. Figures 13 and 14 show the reduction in OASPL from the baseline case caused by the filament. These figures emphasize the high levels of attenuation obtained in the regions dominated by screech. In the upstream grid, attenuation levels as high as 24dB are observed, while Figure 14 indicates that the screech harmonic has been attenuated by an average of 15-16dB. Note also the effect that the filament has further downstream in the region dominated by turbulent mixing noise. In this region, the OASPL is reduced from an average of 140dB to 129dB. This provides further evidence that the filament is successful in attenuating turbulent mixing noise in addition to that indicated by the narrowband spectra.

Further evidence of the shift of the dominant noise generation mechanism from screech to turbulent mixing is a displacement of the peak OASPL level downstream of the nozzle lip. Notice in the baseline case that the peak OASPL occurs very close to the nozzle lip, which would indicate screech to be the dominant noise generation mechanism. However, in the treated case, the peak OASPL level has shifted away from the nozzle lip by a distance of 6-7 diameters in the downstream direction. A peak OASPL level in this downstream region would indicate turbulent mixing to be the dominant noise generation mechanism. This transition from a screech dominated near field to turbulence dominated is collaborated by the narrowband spectra presented in Figures 3, 4, and 8.

In order to more completely evaluate the centerline filament performance, sound mappings were also performed with the jet operating at a Mach number of 0.9. This condition more closely simulates the operating condition of commercial aircraft engines at takeoff, which is the primary focus of most current jet noise research. Figures 19-22 show the near field plots obtained for this operating condition. As subsonic jets are dominated by turbulent mixing noise, these results exhibit the expected form[7]. The strong directional gradients seen in the supersonic jet are replaced by fairly smooth contours showing sound propagating primarily into the rear arc. At first, it appears that the filament effect is limited to the region near the nozzle lip, where it appears to smooth the sound field and weaken the gradients just downstream of the nozzle lip. However, a plot of the OASPL reduction, as shown in Figure 23, reveals that the filament is more effective than Figures 19-22 would initially indicate. The filament is successful in reducing the turbulent mixing noise in the rear quadrant by an average of about 1dB. This is in agreement with that data gained by others investigating the filament effectiveness on a subsonic jet[8]. As the inlet angle increases, the OASPL reduction increases to a maximum in excess of 2dB. While not as dramatic a reduction as was observed in the supersonic jet, this level of reduction can be regarded as significant for a subsonic jet. It is reasoned that additional reduction in turbulent mixing noise could be realized by attaching multiple filaments around the nozzle periphery and allowing them to interact with the jet shear layer. Given the lack of significant large- scale structures such as shocks in the core of the subsonic jet, it is likely that only the portion of the centerline filament extending beyond the potential core absorbs significant energy from the flow. For this reason, future efforts with subsonic jets will focus on filaments attached to the nozzle periphery where the entire filament length can interact with the flow structures.

The narrowband spectra results together with the near field mapping results clearly address goal (3), which was to determine attainable flow enhancement/modification. This report documents the degree of noise reduction achievable for a range of operating conditions.

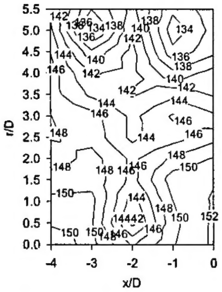


Figure 9: Baseline OASPL (dB re 20μPa) Upstream Grid, M=1.3, Cold Jet

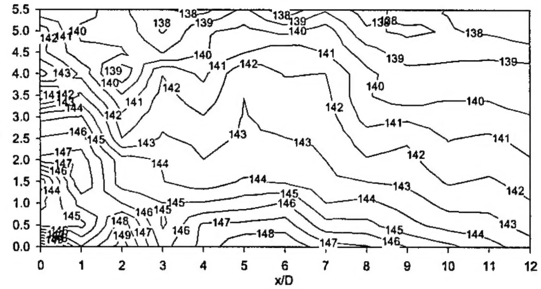


Figure 10: Baseline OASPL (dB re 20μPa) Downstream Grid, M=1.3, Cold Jet

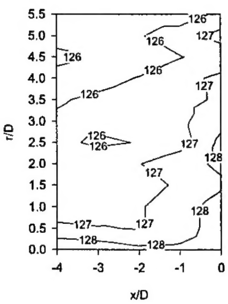


Figure 11: Filament OASPL (dB re 20μPa) Upstream Grid, M=1.3, Cold Jet

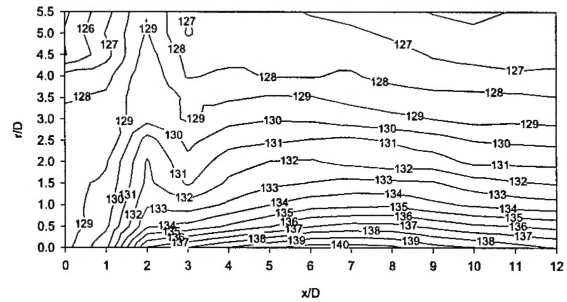


Figure 12: Filament OASPL (dB re 20μPa) Downstream Grid, M=1.3, Cold Jet

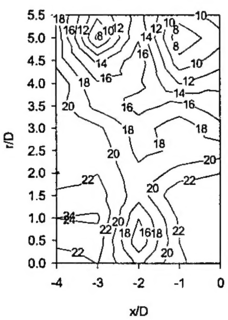


Figure 13: OASPL Reduction (-dB re 20μPa) Upstream Grid, M=1.3, Cold Jet

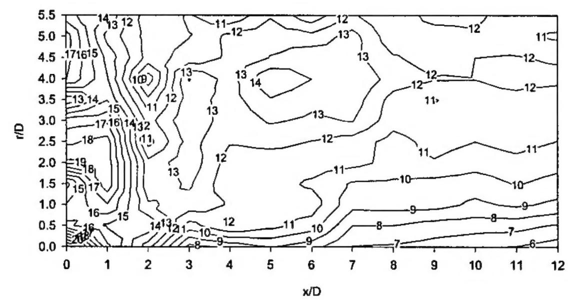


Figure 14: OASPL Reduction (-dB re 20μPa) Downstream Grid, M=1.3, Cold Jet

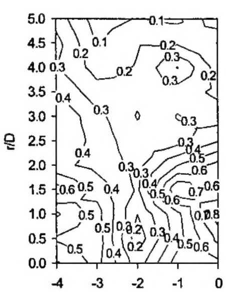


Figure 15: Fundamental Screech Amplitude Baseline, Upstream Grid, M=1.3, Cold Jet

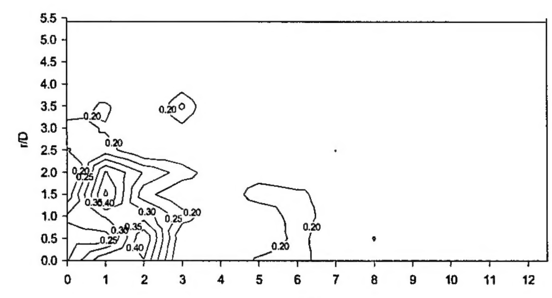
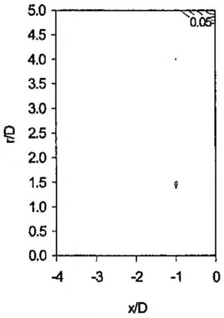


Figure 16: Fundamental Screech Amplitude (St=0.3) Baseline, Downstream Grid, M=1.3, Cold Jet



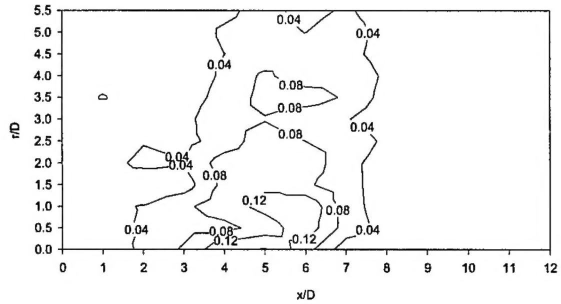
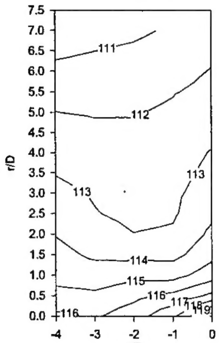


Figure 17: Screech Harmonic Amplitude Baseline, Upstream Grid, M=1.3, Cold Jet

Figure 18: Screech Harmonic Amplitude (St=0.6) Baseline, Downstream Grid, M=1.3, Cold Jet



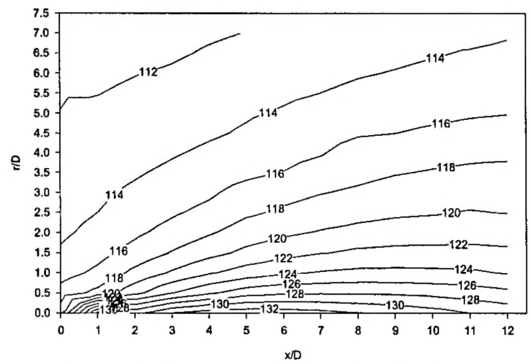
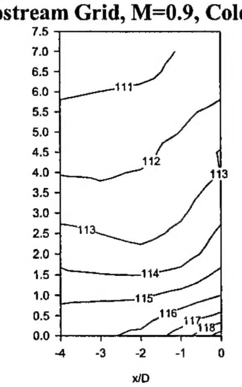


Figure 19: Baseline OASPL (dB re 20μPa) Upstream Grid, M=0.9, Cold Jet

Figure 20: Baseline OASPL (dB re 20μPa) Downstream Grid, M=0.9, Cold Jet



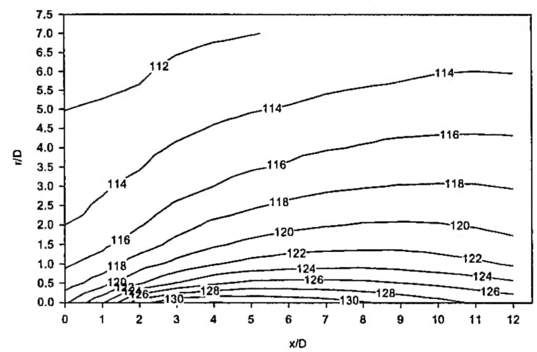


Figure 21: Filament OASPL (dB re 20μPa) Upstream Grid, M=0.9, Cold Jet

Figure 22: Filament OASPL (dB re 20μPa) Downstream Grid, M=0.9, Cold Jet

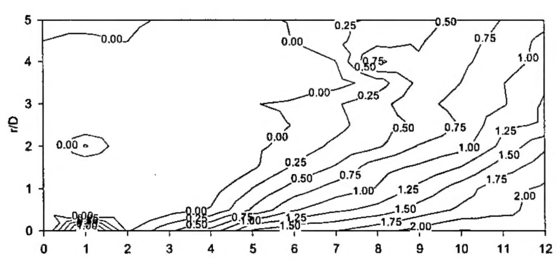


Figure 23: OASPL Reduction (-dB re 20μPa) Downstream Grid, M=0.9, Cold Jet

Flowfield Analysis

In order to address goal (1), and gain better understanding of the physical mechanisms responsible for the observed noise reduction, detailed flowfield analysis was performed using a stereoscopic PIV system. Since the filament proved to be most effective at a Mach number of 1.3, this condition was selected for further investigation. The ensemble-averaged axial velocity field for the baseline case is shown in Figure 24. The shock cell structure is clearly visible as are the strong velocity gradients in and near the shocks and expansion waves. Note that there are three distinct shocks visible with a spacing of approximately 25-30mm. Figure 25 shows the ensemble averaged axial velocity field obtained with an optimally sized filament attached. The empty area near the centerline of the jet was blocked by the filament.

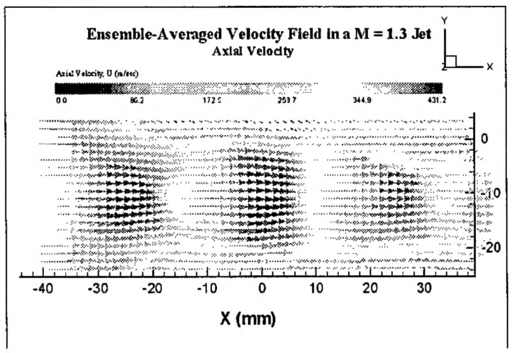


Figure 24: Axial Velocity Field of Mach 1.3, Cold Jet Baseline

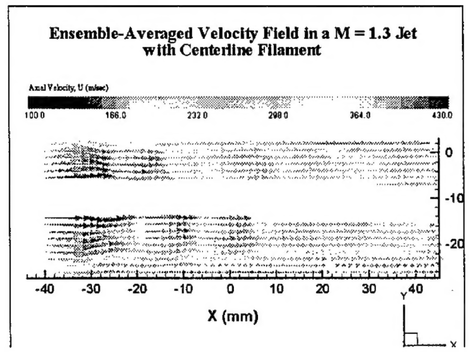


Figure 25: Axial Velocity Field of Mach 1.3, Cold Jet Optimal Sized

Immediately noticeable is the fact that the filament has significantly weakened the shock cell structure and reduced the spacing. This data collaborates Shadowgraph results that were obtained previously by other researchers[9]. It is quite likely that the physical mechanism responsible for the filament's effective screech attenuation lies in this ability to modify and weaken the shock cell structure. Powell first identified the screech phenomenon as a feedback loop sustained by the excitation of large-scale structures near the nozzle lip[10]. As this feedback loop is sustained by acoustic radiation generated through an interaction of the large-scale flow structures with the shock cells, a weakening of the shock cells would explain the observed decrease in screech amplitude[10-12]. This would also explain the reduction in high frequency shock associated noise seen in the narrowband spectra, as this noise component is also a product of an interaction of large-scale flow structures with the shock structure. Note also, that the filament has increased the spread of the jet and reduced the downstream velocities. Both of these observations imply improved mixing of the jet with the ambient flow, and provide a physical explanation for the reduction seen in turbulent mixing noise.

Plots of the jet turbulence intensity further illustrate the increased spreading caused by the filament. The low velocity core region can be seen to extend further in the radial direction in Figure 27 than in the baseline case shown in Figure 26. This data also indicates that there may be reduced turbulence in the shear layer, as seen approximately 30-70mm downstream of the exit plane on the lower edge of the jet. However, due to the increased spread of the jet, and thus the outward displacement of the shear layer, it is

difficult to make a conclusive judgment on changes to the shear layer, from the available data.

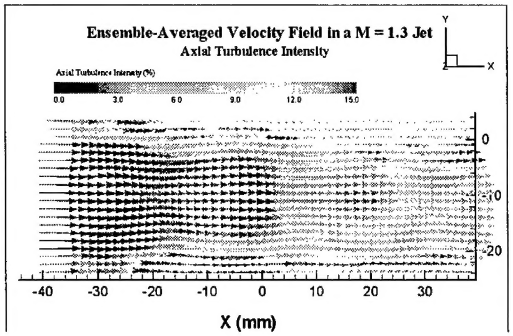


Figure 26: Turbulence Intensity of Mach 1.3, Cold Jet Cold Jet Baseline

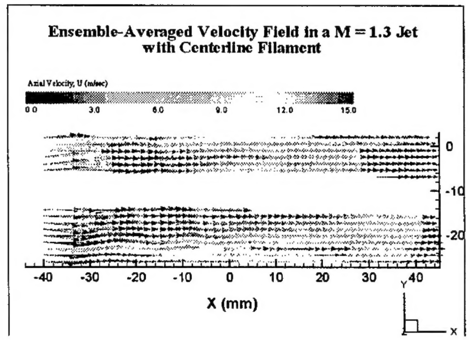


Figure 27: Turbulence Intensity Field of Mach 1.3, Optimal Sized Filament Attached

The flowfield data presented for the Mach 1.3, cold jet clearly illustrate the filament's ability to modify the structure of the jet. More importantly, these modifications can each be tied physically to the observed reductions in acoustic emissions, as prescribed in program goal (1).

Summary and Conclusions

It is the opinion of the investigators involved that this research program can be considered successful. Specifically, each of the program goals was met. First, a parametric study succeeded in determining an optimal filament configuration for maximum noise attenuation. For an underexpanded, supersonic jet, this configuration proved to be filament with a length of at least 3 nozzle diameters and thickness of at least 4% of the nozzle diameter. Based on data obtained with such a filament, peak level attenuations in the range of 19-32dB were recorded for supersonic jets and screech tones were completely suppressed. A study of the effect of jet temperature on the filament performance indicated that for the moderate temperatures investigated, the filament performance is enhanced by increased temperature. In order to better understand the overall spatial effect of the filament, extensive near field mapping was conducted for both M=1.3 and M=0.9 jets. The filament was successful in eliminating the strong directional gradients typically associated with an underexpanded jet, and converting the sound field from a screech dominated field to a turbulence mixing dominated field. Reductions as high as 24dB were observed in regions dominated by screech. Also, the peak OASPL in the near field was reduced by 12dB and the OASPL was reduced by approximately 10dB in the downstream region dominated by turbulent mixing. In addition to this supersonic jet, the near field was also mapped for a Mach 0.9 cold jet. The results indicated a fairly significant reduction in turbulent mixing noise of up to 2dB could be obtained with the centerline filament. Flow field analysis of the M=1.3 jet by stereoscopic PIV was successful in correlating the measured reductions in noise to physical changes in the flowfield. Specifically, the effectiveness with which the filament attenuates screech and broadband shock associated noise lies in its ability to modify and weaken the shock cell structure in the jet core.

Technology Transfer

In addition to the results obtained at Louisiana State University, experiments were also conducted at the Boeing INTF to evaluate the ability of the filament to suppress noise. These tests focused primarily on the filament effect on high subsonic cold flow jets.

Future Plans

The work described above concludes the third and final year of grant/contract number F49620-96-1-0378. It is the opinion of the investigators involved that the work can be considered a success as all of the initial objectives were achieved. This work will be continued at the University of Cincinnati as a joint venture with General Electric Aircraft Engines.

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